

An aerial photograph of the Fermilab facility, showing various buildings, parking lots, and green spaces. The image is slightly blurred and has a semi-transparent text overlay.

Monte Carlo Study of Pion Absorption in LArIAT

Andrew Olivier for the LArIAT
Collaboration

APS April Meeting

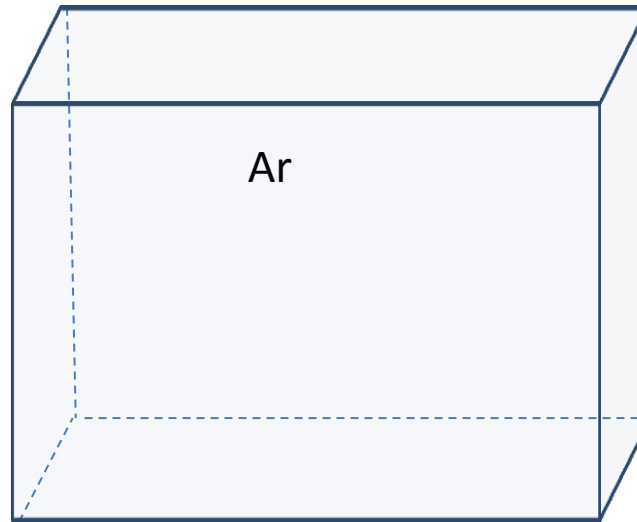
April 18, 2016

The Deep Underground Neutrino Experiment

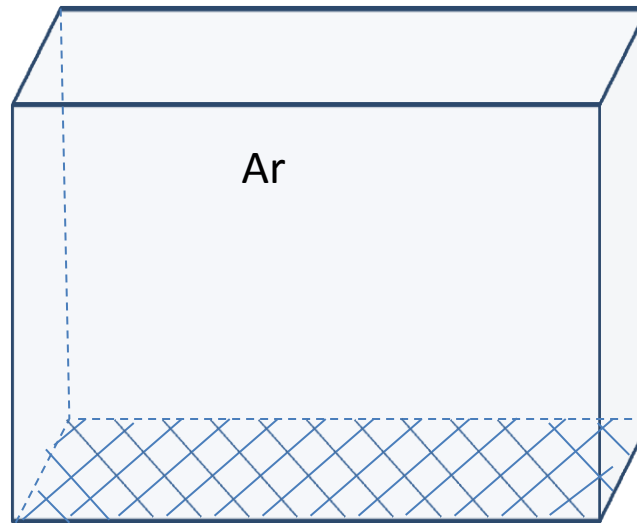
Credit: DUNE Collaboration

- The **D**ee**P** **U**nder**g**round **N**eutrino **E**xperiment will precisely measure parameters of neutrino oscillations in a beam of high energy neutrinos sent from Fermilab in Batavia, IL to Lead, SD
 - Plans to use liquid argon time projection chamber (LArTPC) technology to capture energy deposited and reconstruct topologies of neutrino interactions
 - Requires precise knowledge of responses of LArTPCs to various charged particles
 - Cross sections are needed for interactions like **pion absorption** and **pion charge exchange** that change the final state of a neutrino interaction
 - Photon showers from neutral pion decays can be mistaken for electrons from electron neutrino interactions if one photon does not convert in the TPC

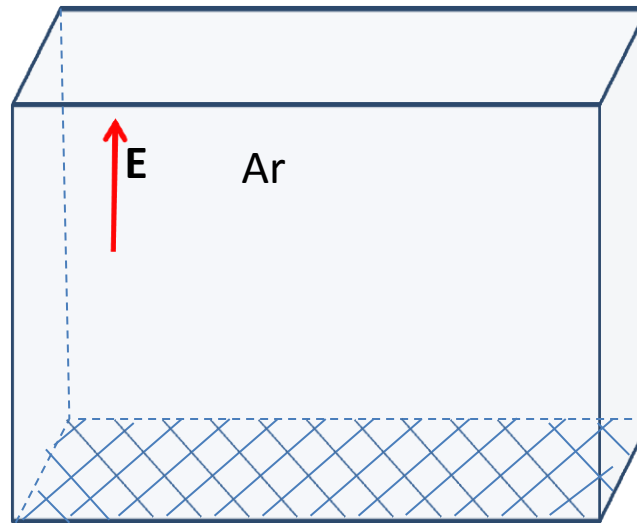
How Time Projection Chambers Work



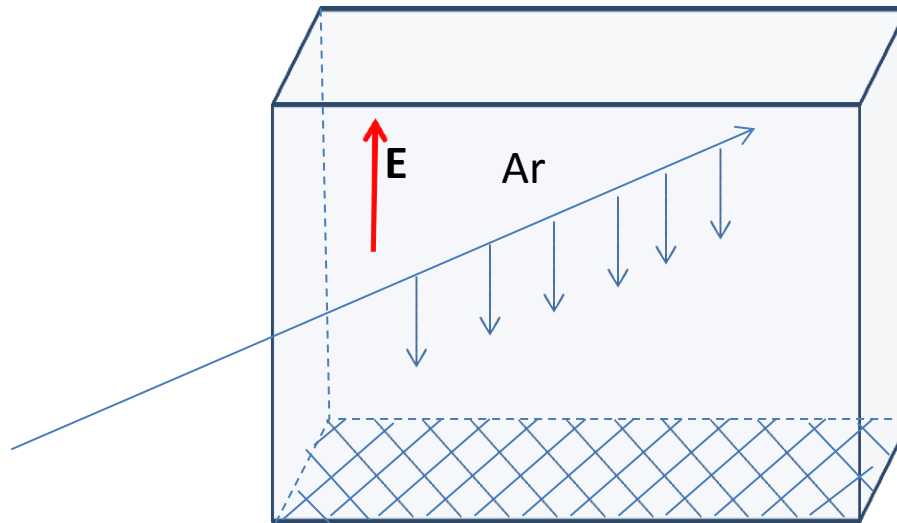
How Time Projection Chambers Work



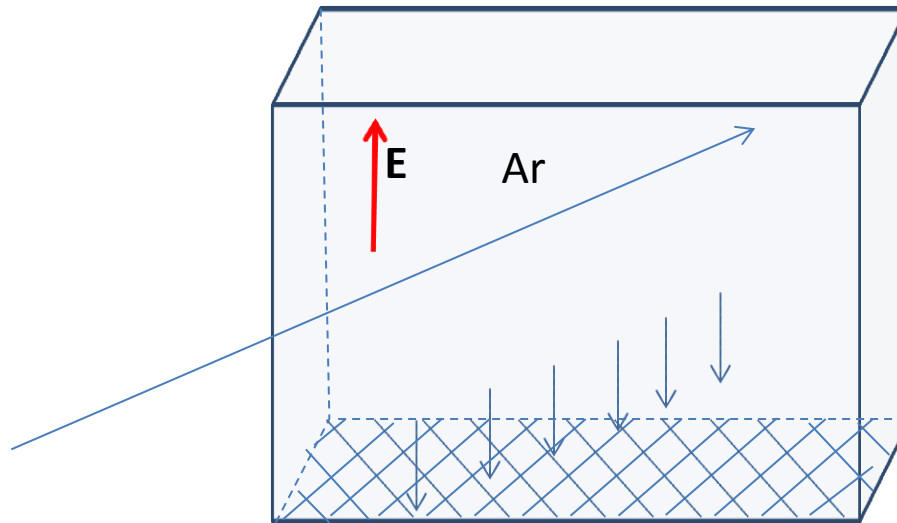
How Time Projection Chambers Work



How Time Projection Chambers Work



How Time Projection Chambers Work

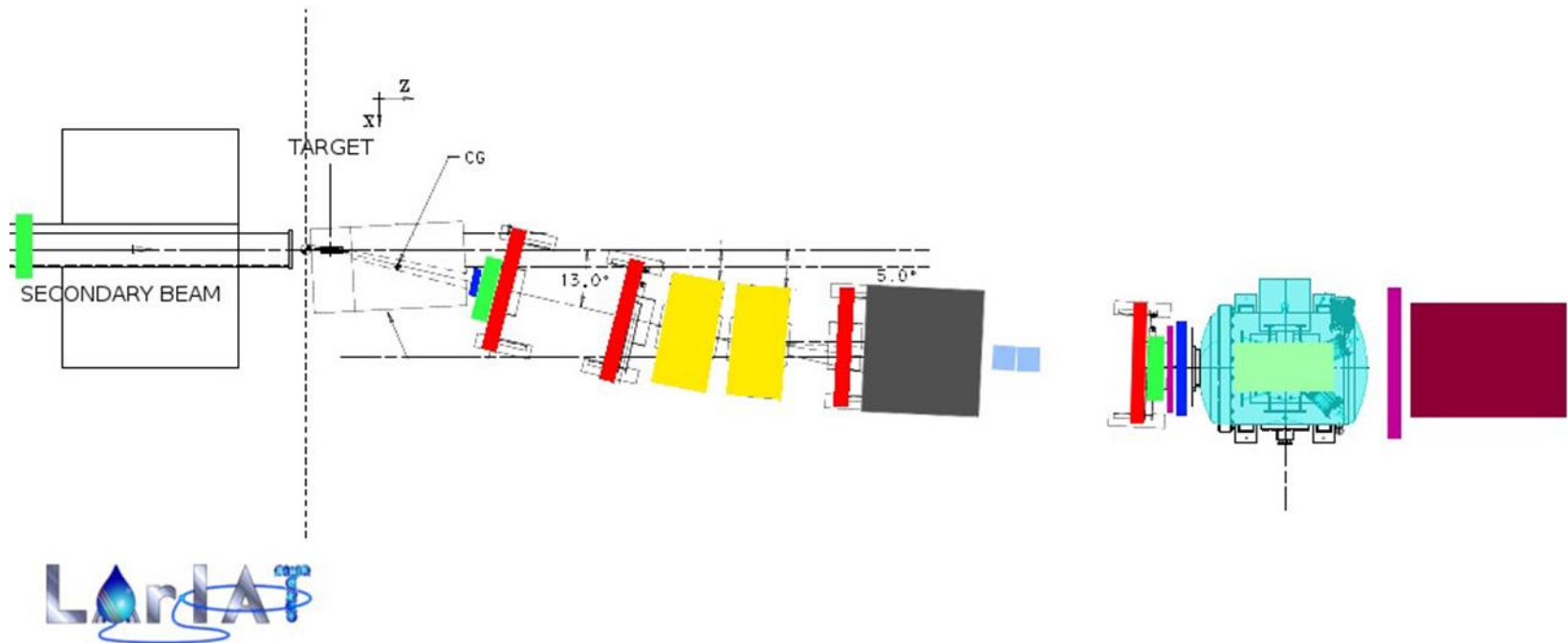


LArIAT

- The **Liquid Argon Time Projection Chamber in a Test Beam** experiment studies charged particle interactions in a LArTPC
 - Exposes a LArTPC to a controlled beam of charged particles
 - Test beam detectors identify beam particles for comparison with TPC
 - Uses a preexisting small TPC: the modified ArgoNeut TPC

LArIAT's Beamline

- Beam of mixed particles produced at start of beamline



LArIAT's Beamline

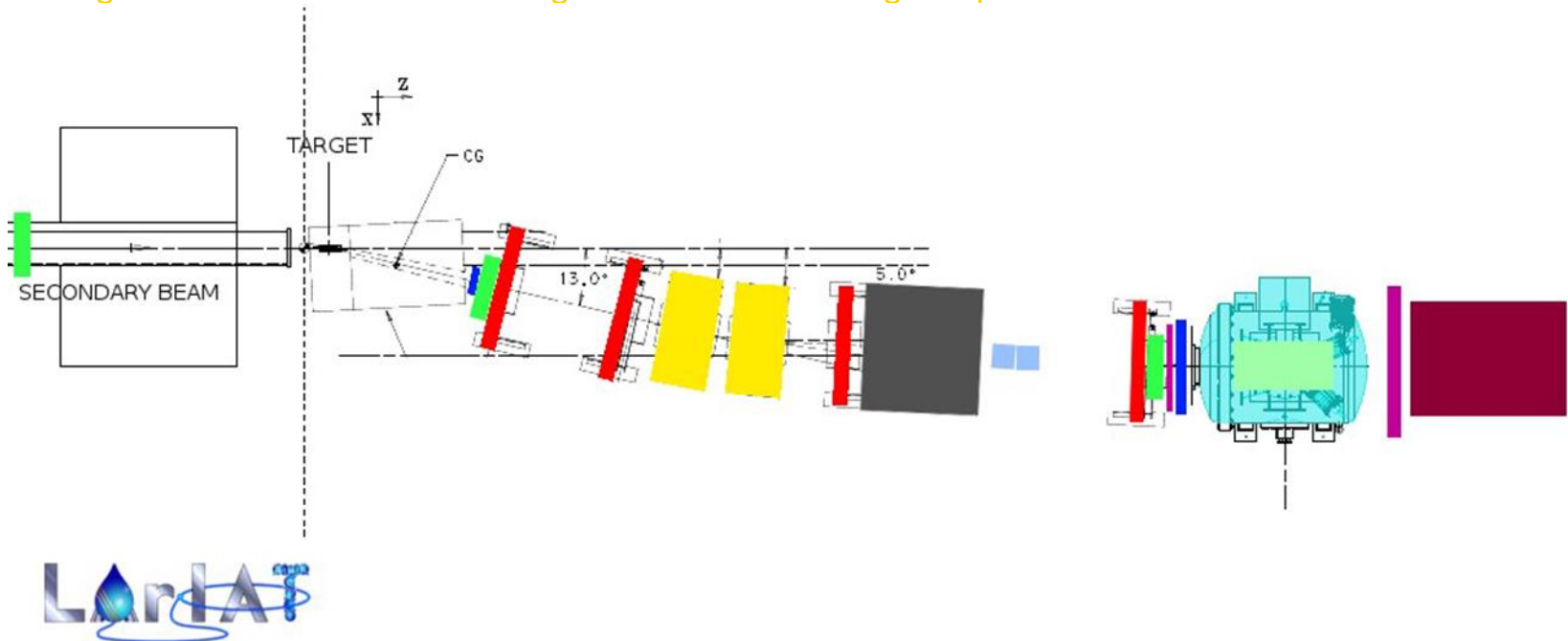
- Beam of mixed particles produced at start of beamline
- Time of Flight detectors determine how long particles took to traverse beamline
- Wire Chambers track positions of particles as they approach the TPC
- Magnets bend beam to select charge and momentum range for particles



- Aerogel detectors measure particles' velocities
- Halo veto detects particles traveling along the beam that may not have been selected by magnets
- LArIAT TPC records images of particle interactions
- Punch through veto detects particles that pass through the TPC
- Muon range stack measures energies of exiting muons based on how much steel they penetrate

LArIAT's Beamline

- Beam of mixed particles produced at start of beamline
- Time of Flight detectors determine how long particles took to traverse beamline
- Wire Chambers track positions of particles as they approach the TPC
- Magnets bend beam to select charge and momentum range for particles



- Aerogel detectors measure particles' velocities
- Halo veto detects particles traveling along the beam that may not have been selected by magnets
- LArIAT TPC records images of particle interactions
- Punch through veto detects particles that pass through the TPC
- Muon range stack measures energies of exiting muons based on how much steel they penetrate
- Together, LArIAT's beamline detectors can identify a particle's species and measure its momentum

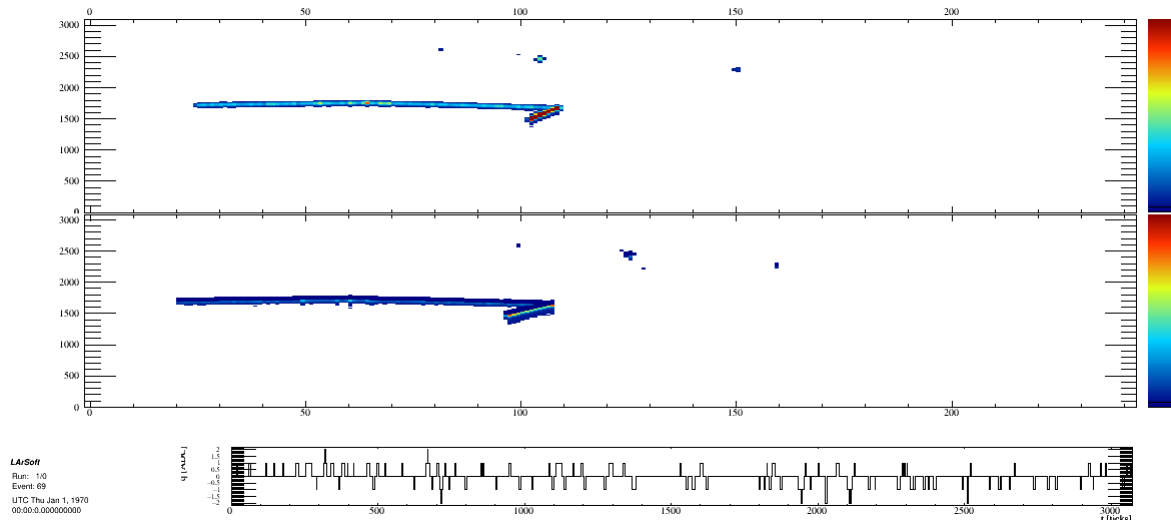
Monte Carlo Sample

- Momenta uniformly distributed between 0 MeV/c and 1500 MeV/c
- 18,000 π^+
- 10,000 of each of μ^+ , p^+ , and K^+
- Started all particles at the beam window
- For this study, all “beamline” values are taken from MC truth information

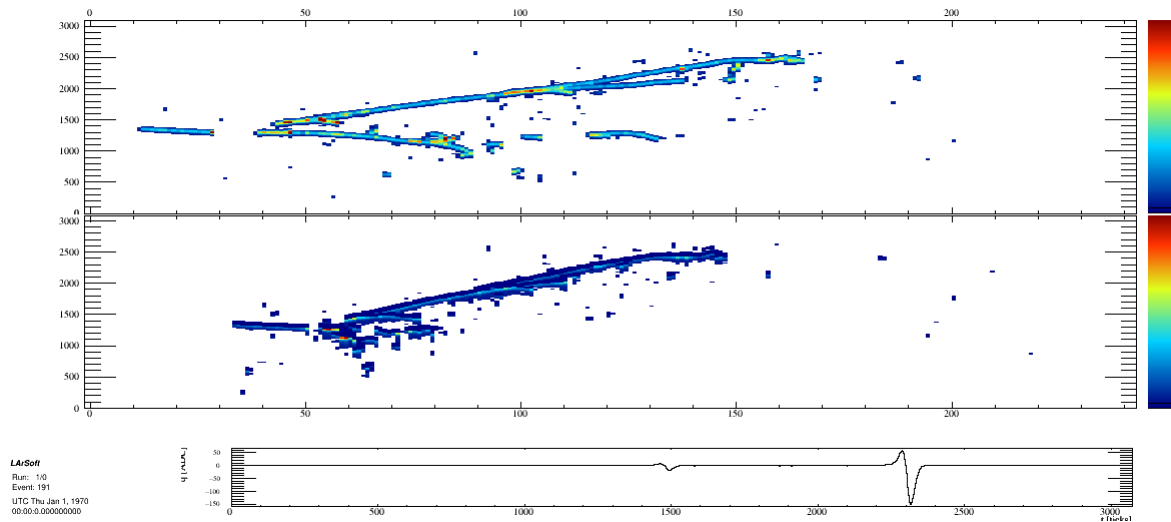
Signal Definition

- An event in which a charged pion enters the TPC and interacts with no charged pions leaving the interaction

Pion Absorption



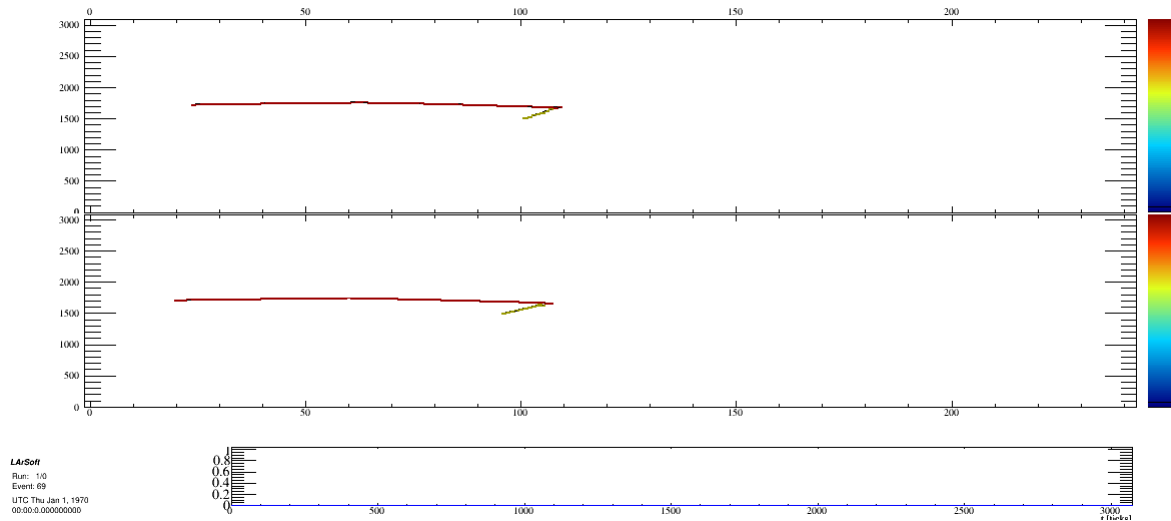
Pion Charge Exchange



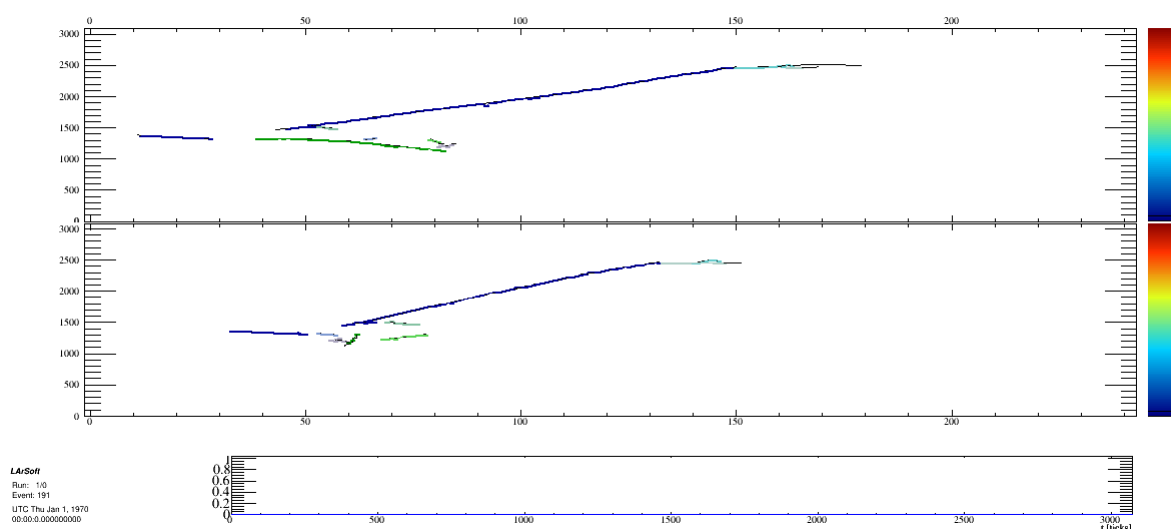
Signal Definition

- An event in which a charged pion enters the TPC and interacts with no charged pions leaving the interaction

Pion Absorption

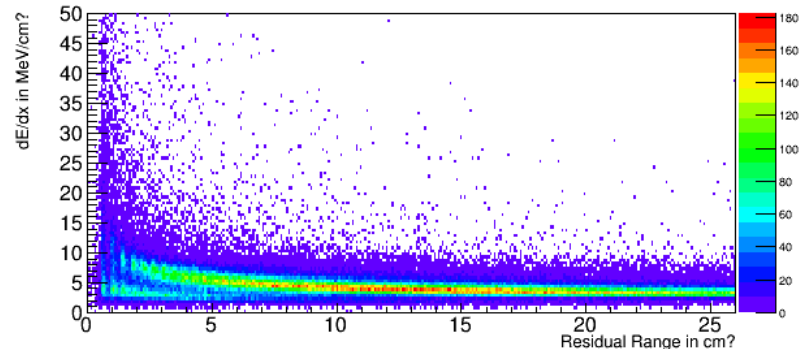
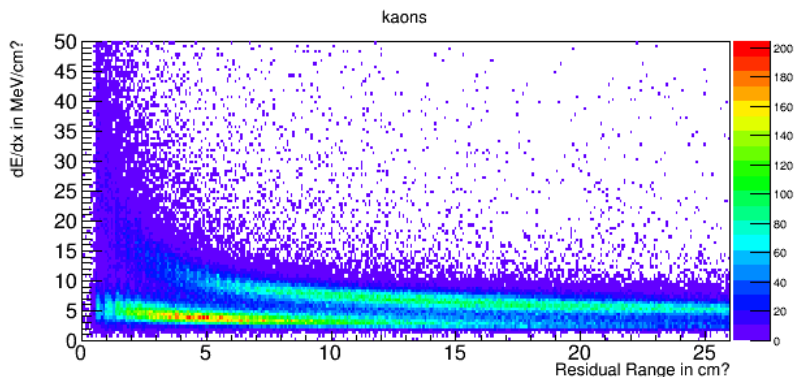
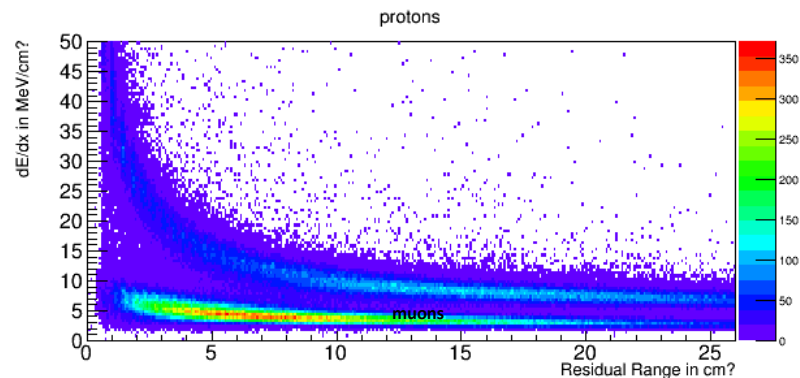
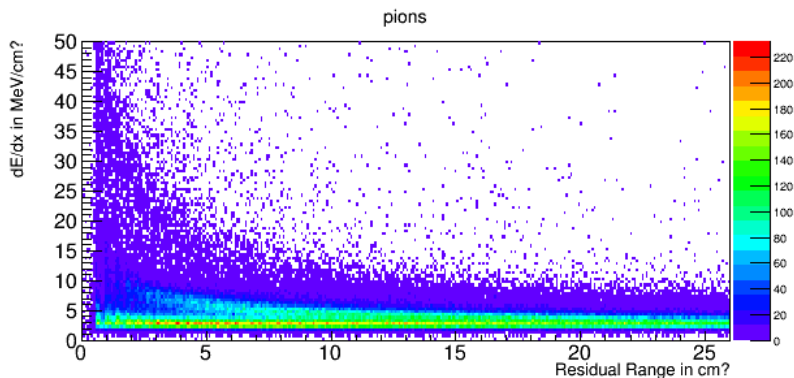


Pion Charge Exchange



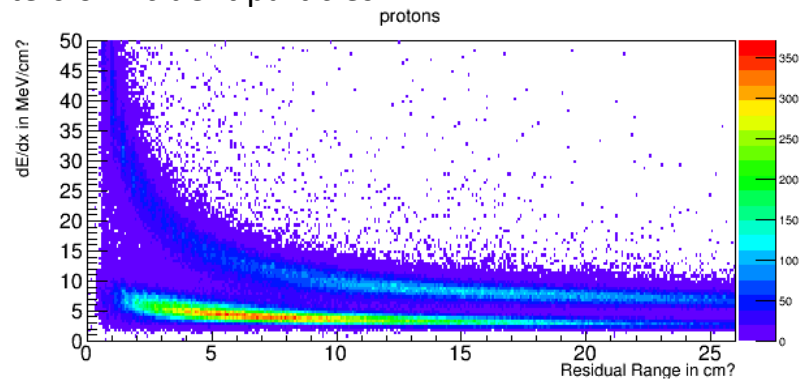
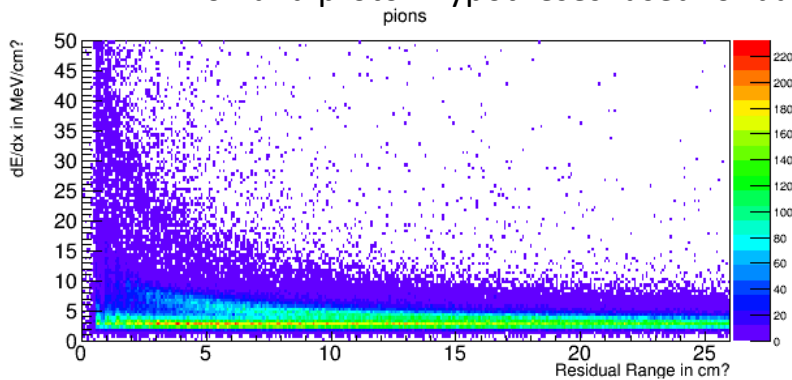
Particle Identification

- Identifying a particle's species is key to identifying an event topology
- Exploits differences in particles' energy loss in matter as a function of distance traveled
- Two populations:
 - Particles that lose all energy by ionization
 - Particles that stop by interacting
- For a track's calorimetry information, calculate a likelihood for each probability density function (PDF) provided
 - Pion, proton, muon, and kaon hypotheses: used for incident particles

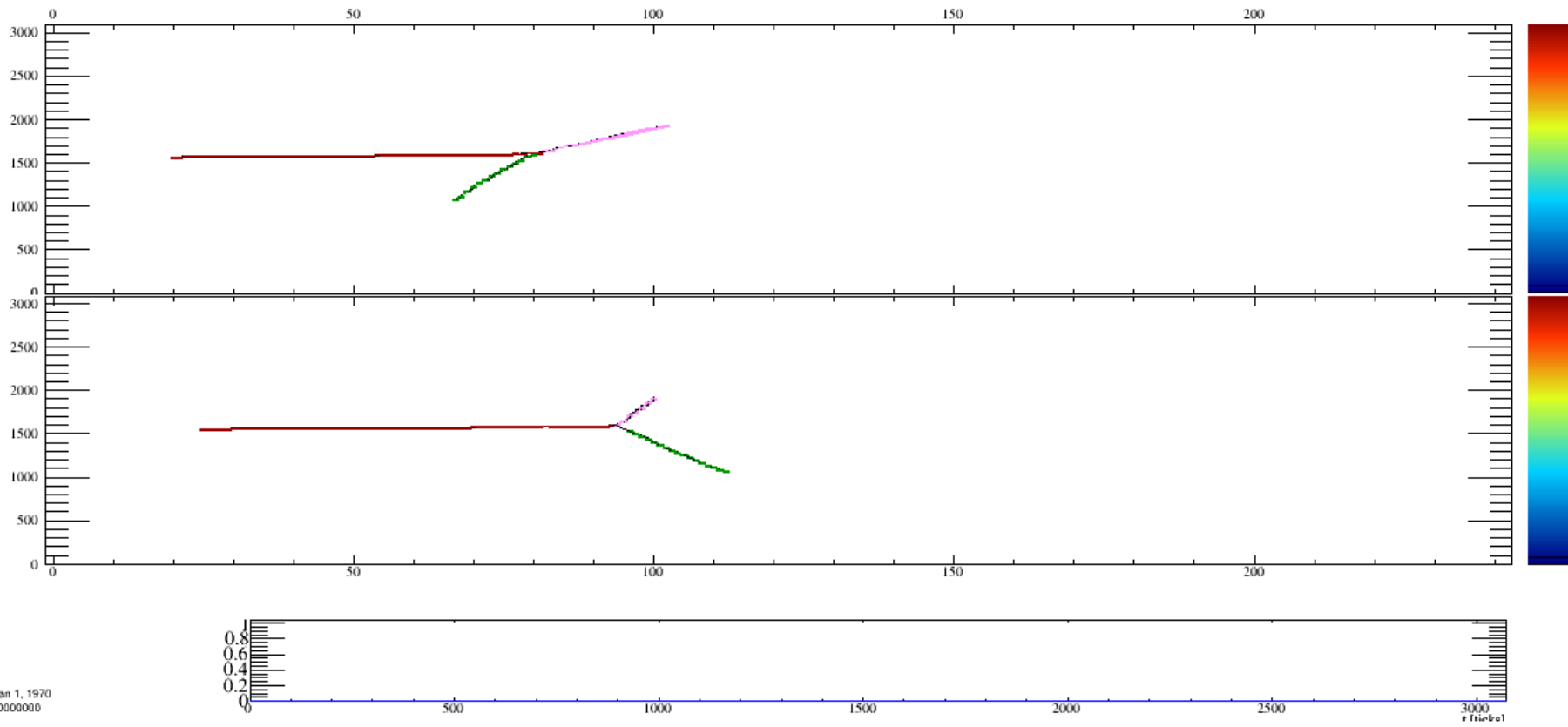


Particle Identification

- Identifying a particle's species is key to identifying an event topology
- Exploits differences in particles' energy loss in matter as a function of distance traveled
- Two populations:
 - Particles that lose all energy by ionization
 - Particles that stop by interacting
- For a track's calorimetry information, calculate a likelihood for each probability density function (PDF) provided
 - Pion, proton, muon, and kaon hypotheses: used for incident particles
 - Pion and proton hypotheses: used for daughters of incident particles

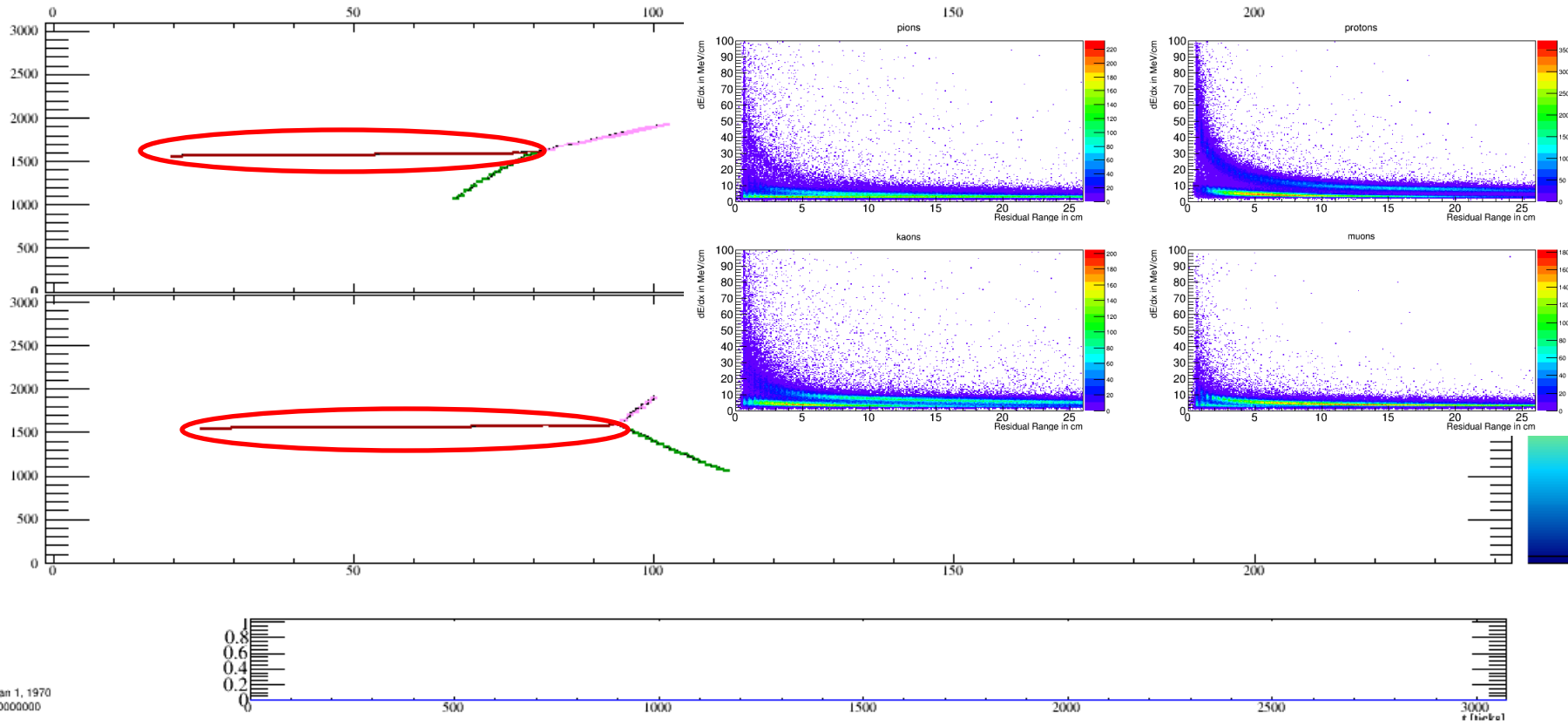


Signal Selection



Signal Selection

- Looking for events with an incident pion



LArSoft

Run: 140

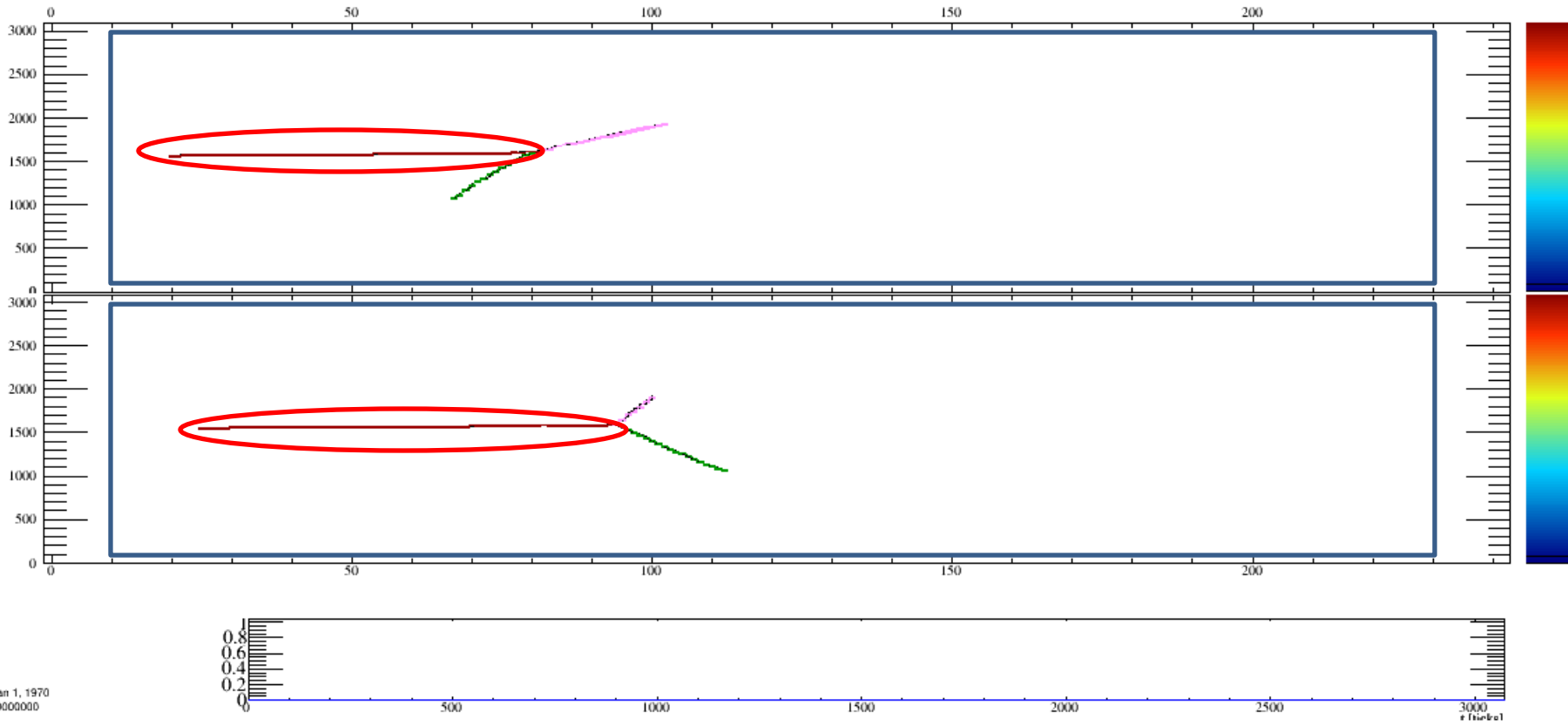
Event: 146

UTC Thu Jan 1, 1970

00:00:0.000000000

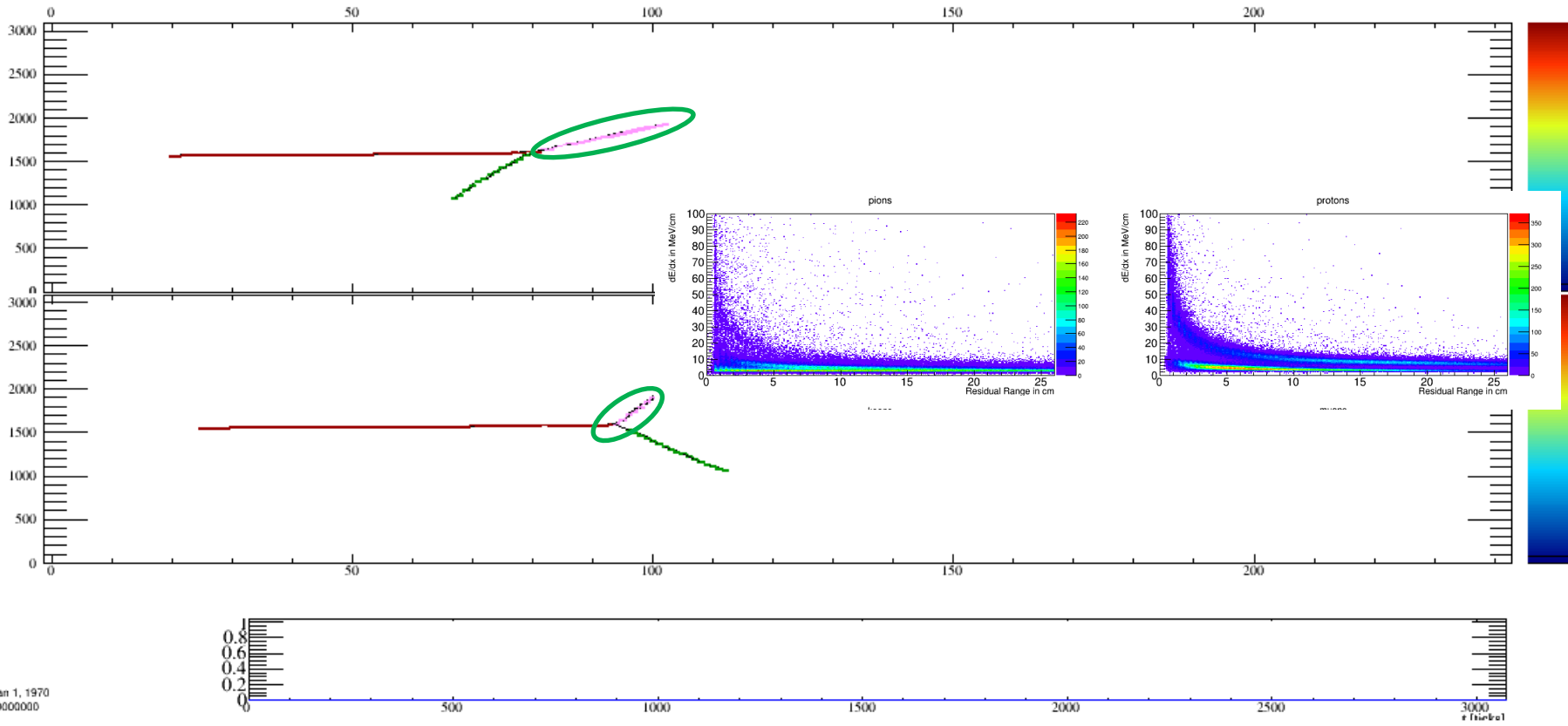
Signal Selection

- Looking for events with an incident pion
- To identify topology, need interaction point in the TPC



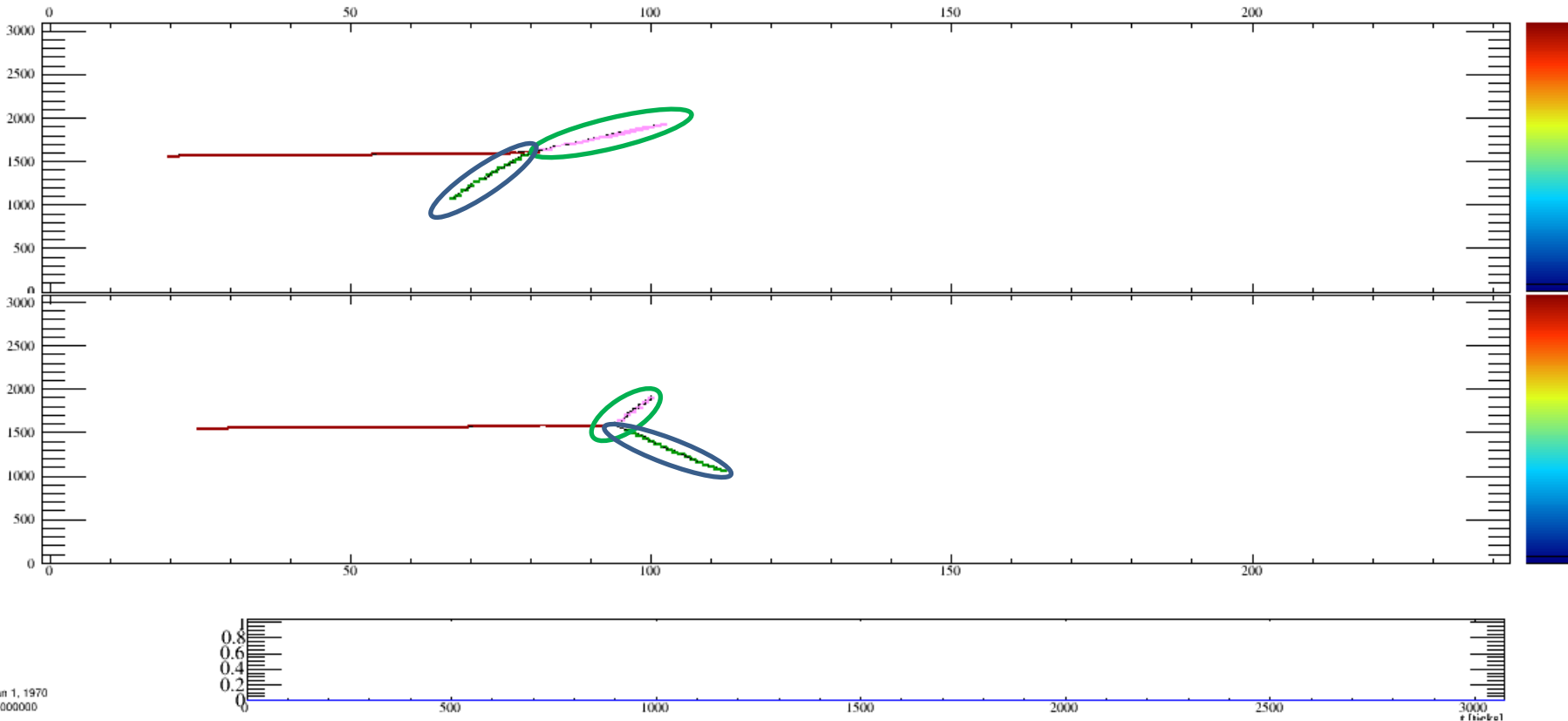
Signal Selection

- Looking for events with an incident pion
- To identify topology, need interaction point in the TPC
- Check that each track is more proton-like than pion-like



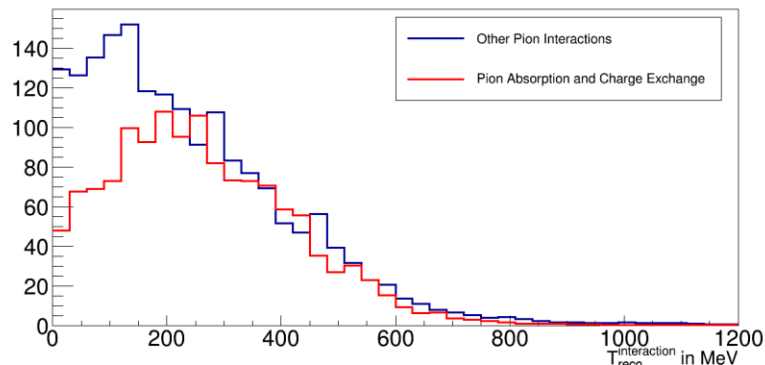
Signal Selection

- Looking for events with an incident pion
- To identify topology, need interaction point in the TPC
- Check that each track is more proton-like than pion-like

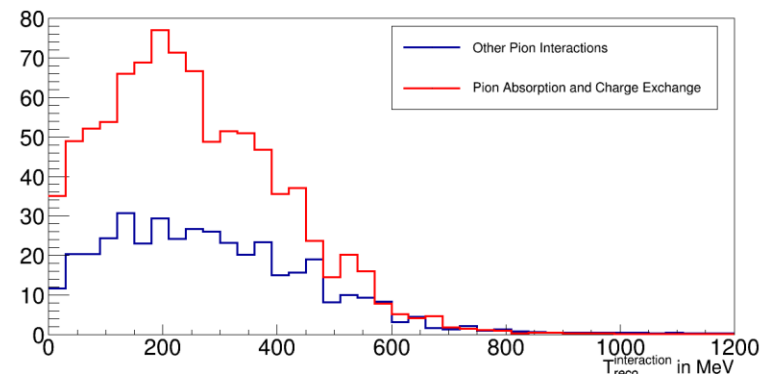


Performance with Reweighting

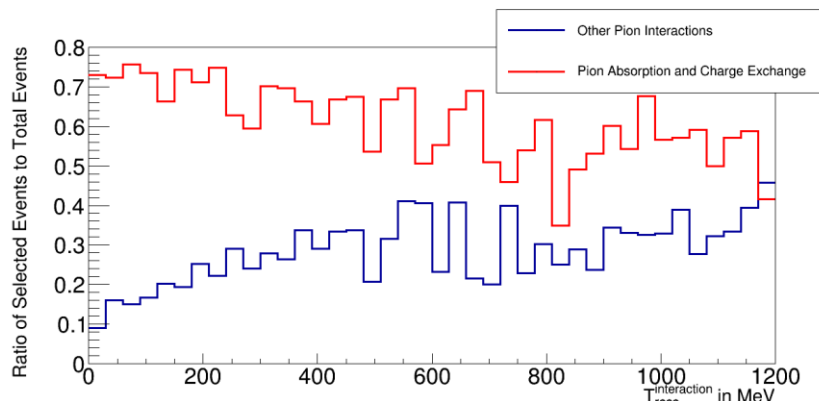
Before Selection



After Selection

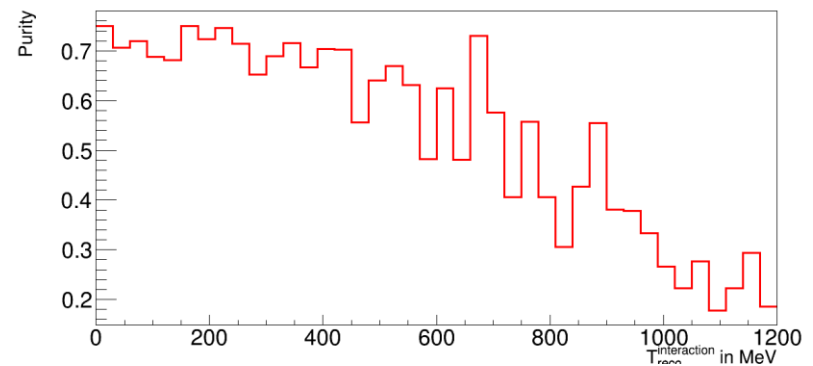


Selection Ratios



Overall Efficiency: 61%

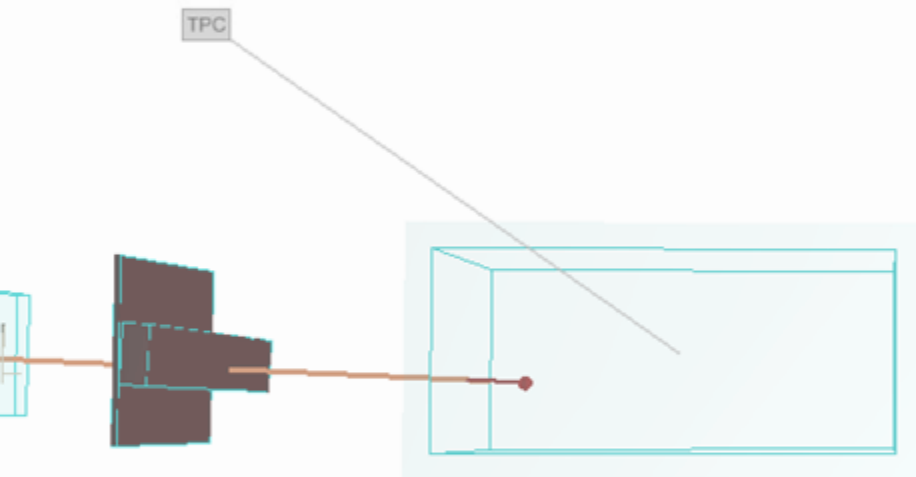
Purity



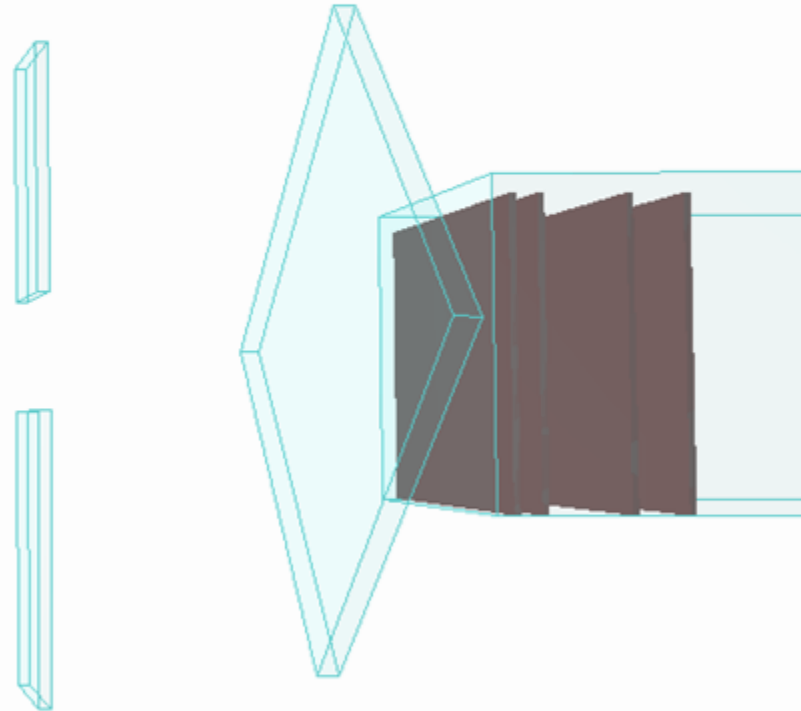
Overall Purity: 54%

Conclusions, and Future Work

- Conclusions
 - Implemented a likelihood-based particle identification method
 - Developed an algorithm to search for pion absorption and charge exchange events based on event topology
 - Demonstrated that this algorithm substantially reduces pion background
 - >60% efficiency
 - >50% purity
- Future Work
 - Extend purity measurement to include other incident particles
 - Extend analysis to measure cross sections for data



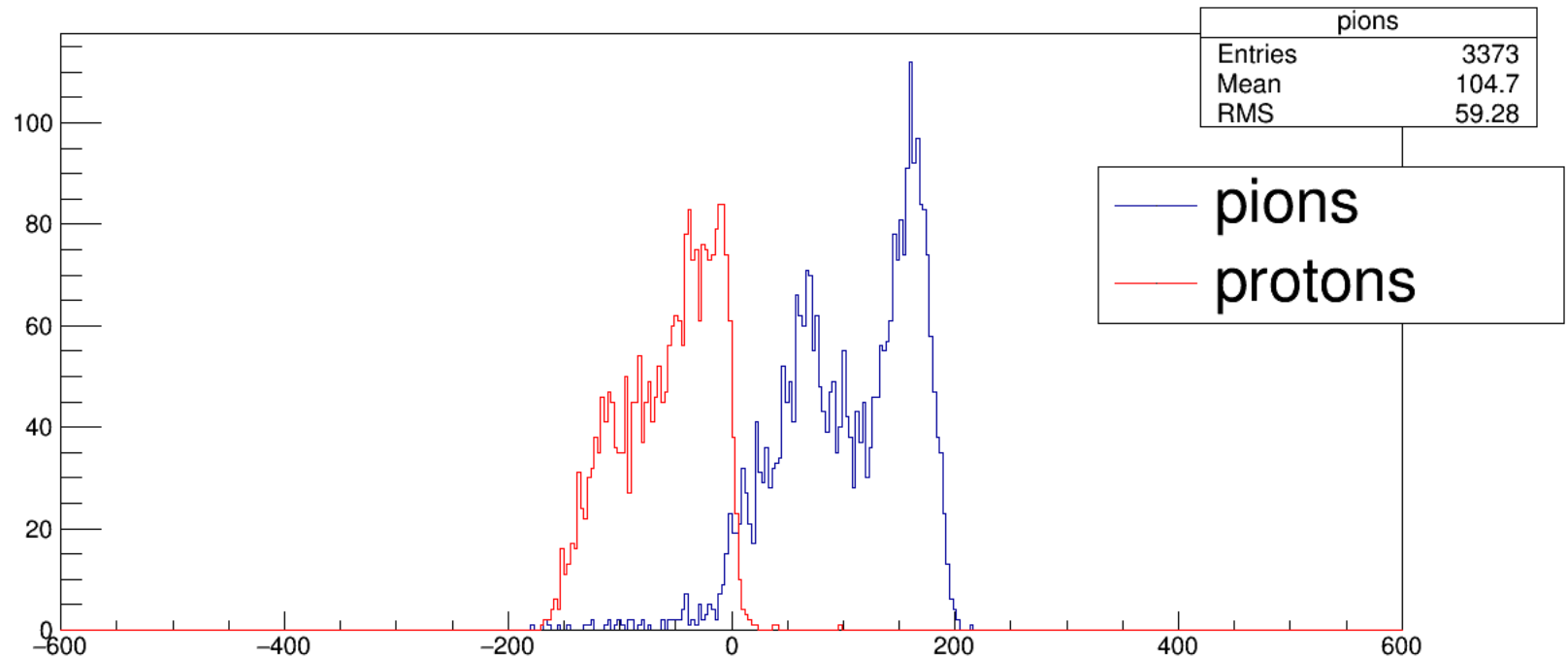
BACKUP SLIDES



Likelihood Definition

- Given some set of reconstructed points $\{(x_i, y_i)\}$ of the form (residual range, dE/dx)
- Given a probability density function $f_{\text{particle}}(x, y)$, a 2-D histogram of dE/dx versus residual range
- $\ln(L_{\text{particle}}) = \sum_{i=1}^n \ln(f_{\text{particle}}(x_i, y_i))$
- To make the best use of double precision values, $\ln(L_{\text{particle}})$ is calculated as a sum of natural logs rather than as a product
- $\ln(L_{\text{pion}}/L_{\text{proton}}) = \ln(L_{\text{pion}}) - \ln(L_{\text{proton}})$ is plotted in likelihood ratio plots

Pion-Proton Separation

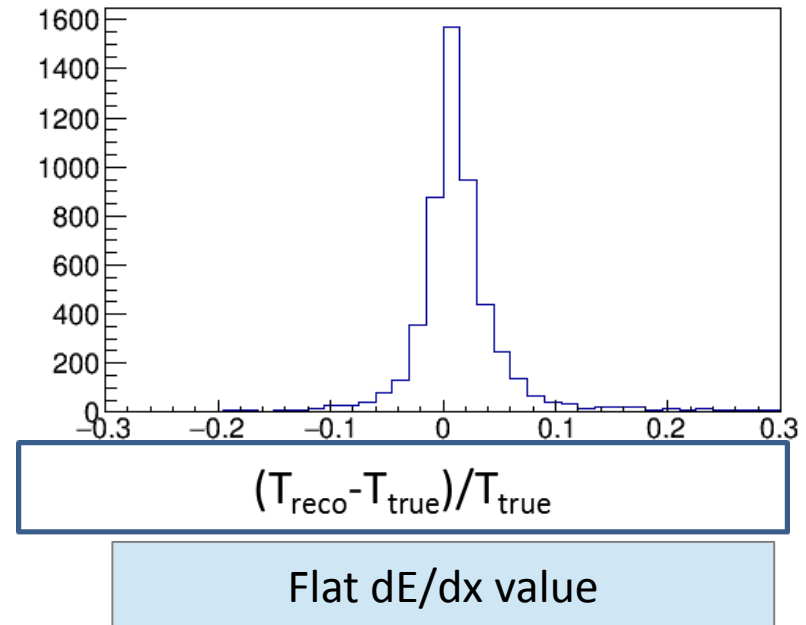
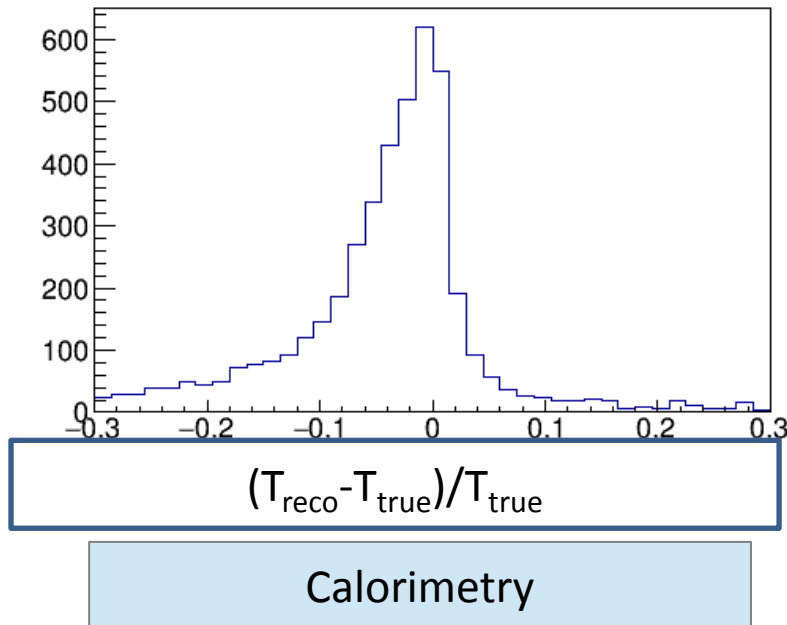


- Pion and proton likelihoods from Monte Carlo samples
- X-axis is $\ln(L_{\text{pion}}) - \ln(L_{\text{proton}})$
- Separation in distributions corresponds to how well pions can be distinguished from protons by PID
- PID picks the hypothesis with the largest likelihood

Kinetic Energy Values in Plots

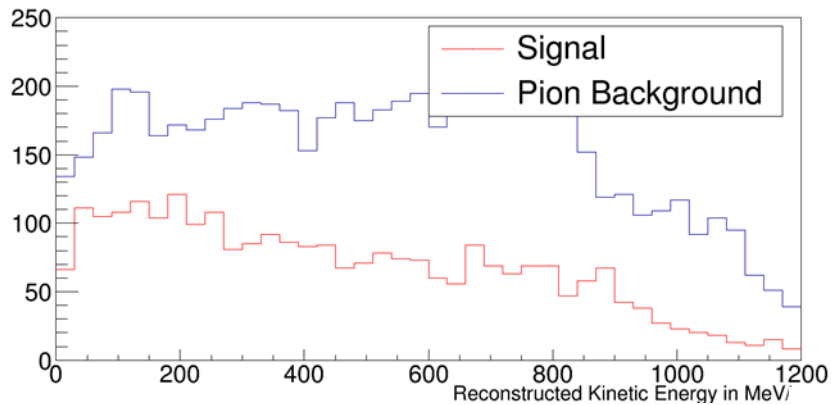
- True Interaction Kinetic Energy = $M_0(\gamma-1)$
- Reconstructed Interaction Kinetic Energy
 - Start with “beamline” kinetic energy: taken from truth kinetic energy at beam window
 - Subtract 8.6 MeV for energy lost between beam window and TPC as done by total pion cross section group
 - Calorimetry provides kinetic energy and total range
 - Option 1: Subtract kinetic energy (in TPC) from
estimated kinetic energy at TPC front face
 - Option 2: Take average dE/dx to be 2.3 MeV/cm for all
pions in this study. Subtract
2.3MeV/cm*Range from estimated
kinetic energy at TPC front face
 - Use method with less deviation from true values

Fractional Interaction Kinetic Energy Resolution

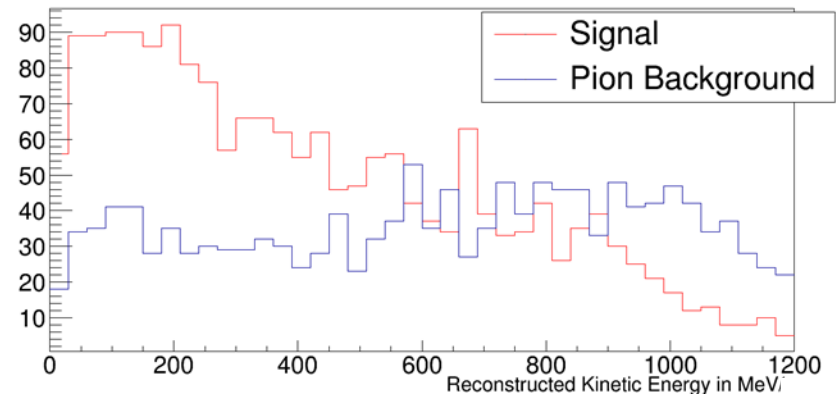


Selection Algorithm Performance on Pions

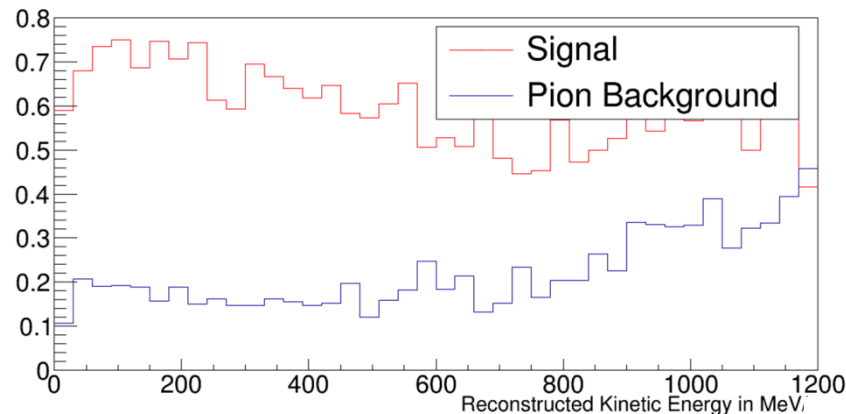
Before Selection



After Selection



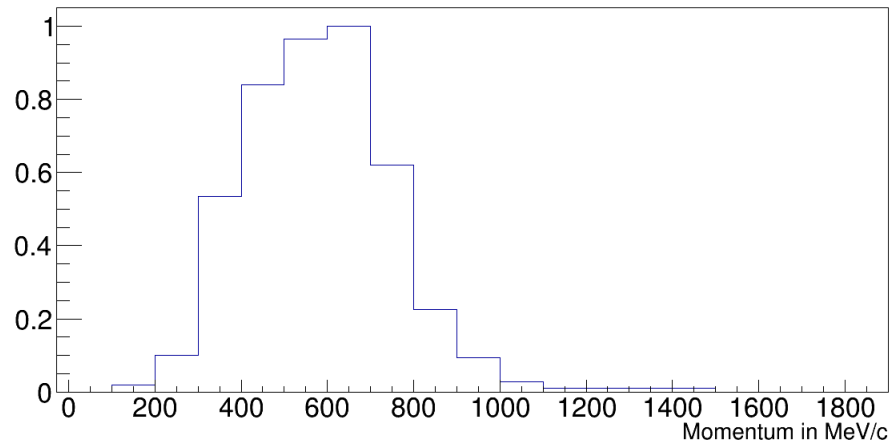
Selection Ratios



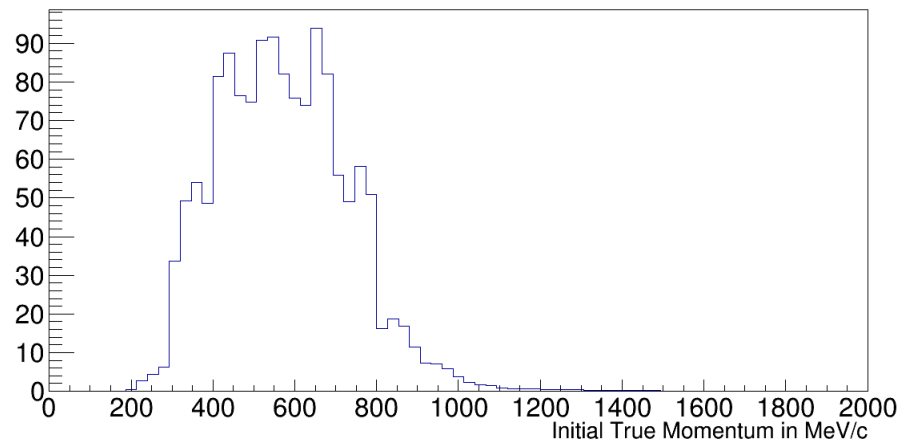
Reweighting

- Flat momentum spectrum of Monte Carlo sample does not reflect LArIAT beam
 - Expect more lower energy pions from LArIAT's beam
 - Expect fewer protons and very few kaons
- Used a reweighting scheme developed by LArIAT Pion Total Cross Section analysis group

Weight Spectrum

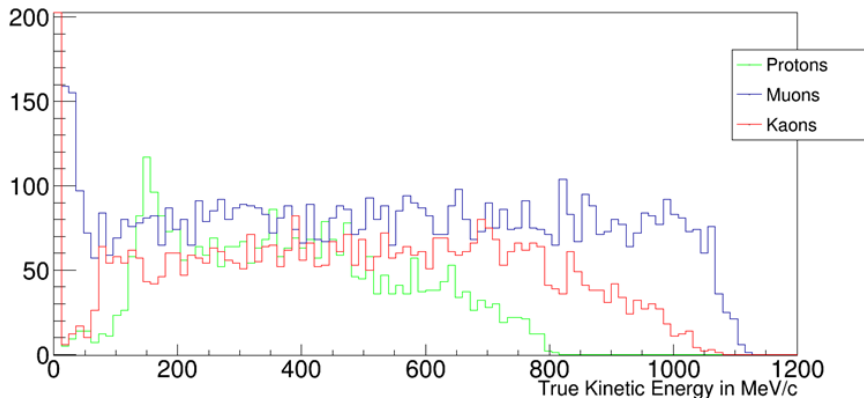


Reweighted Momentum Spectrum

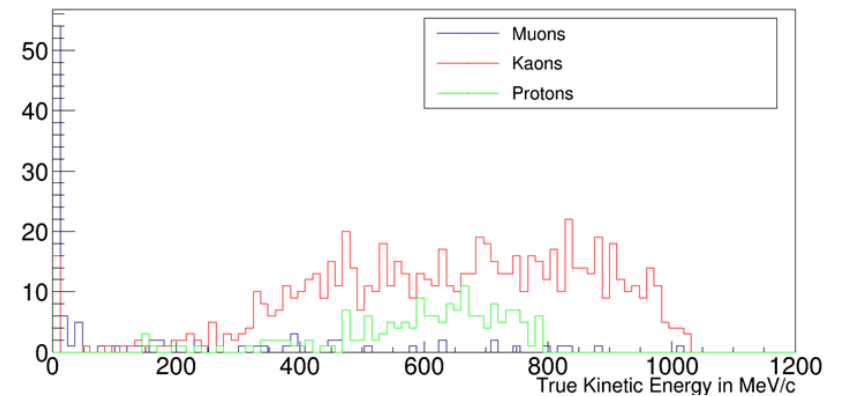


Removing Other Incident Particles

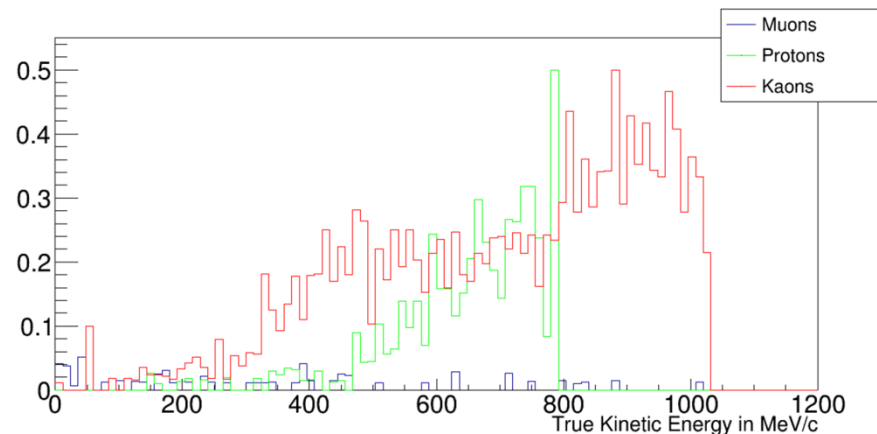
Before Selection



After Selection

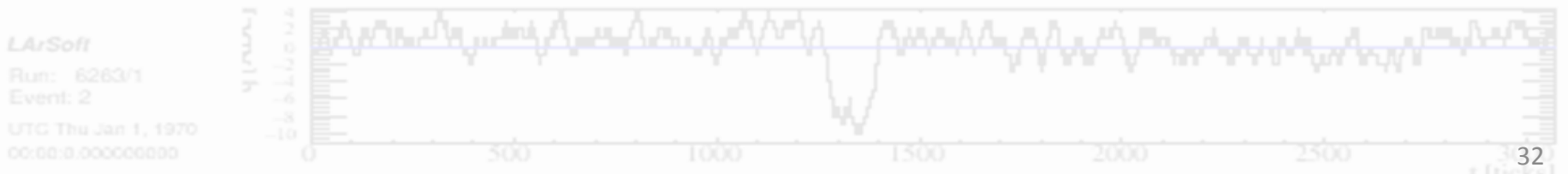


Selection Ratios

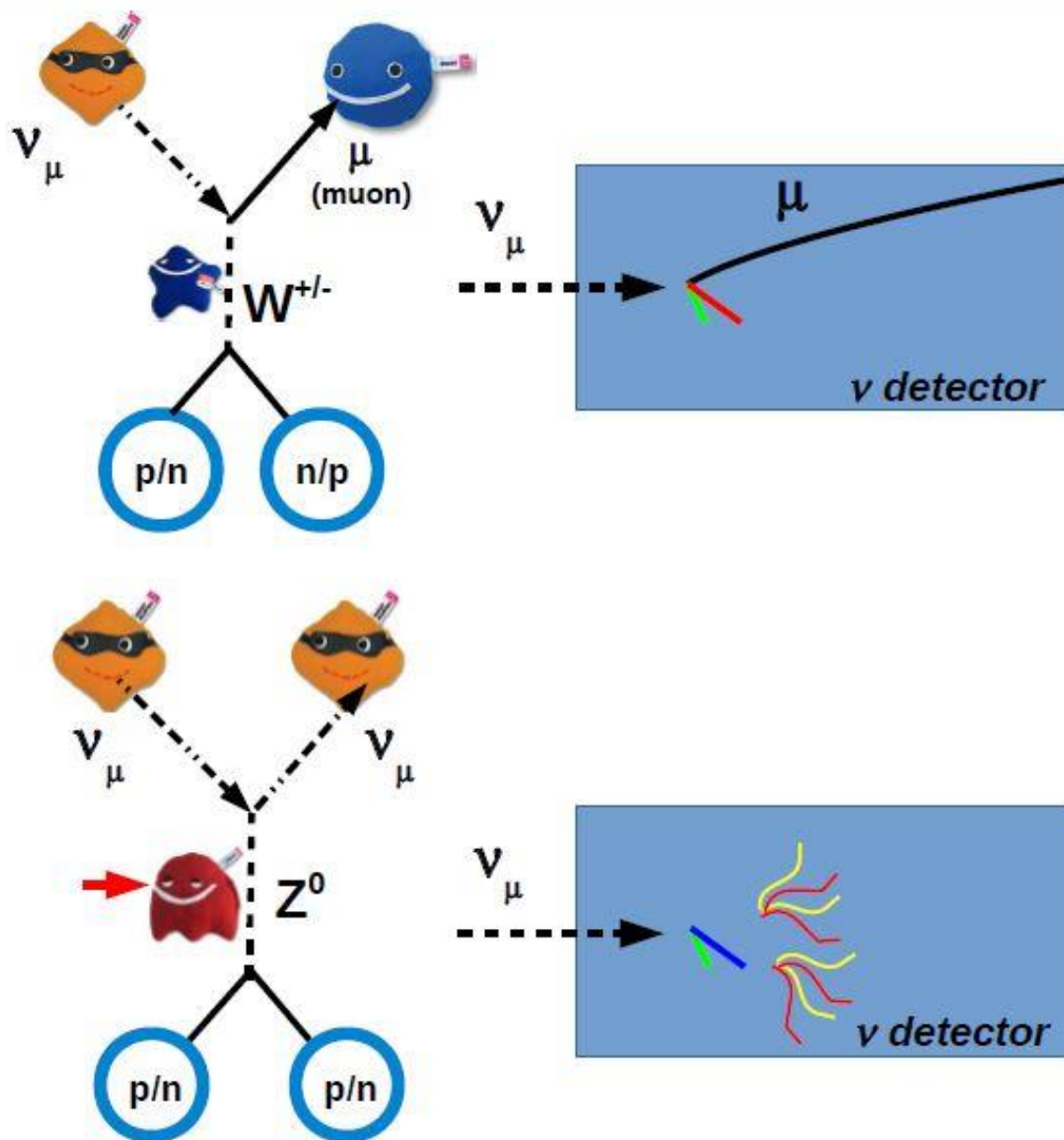


Data Collection

- Run I
 - May-July 2015
 - Beam tuning with help of accelerator division
 - Data currently being analyzed
- Run II
 - Currently in progress
 - Planned for February-July 2016



Motivation: Needs of ν -experiments



- Simplified view of how we do neutrino experiments goes like:
 - Fire a beam of neutrinos into your detector
 - Detect the particles that come out from the interaction
 - Reconstruct the information about the neutrino
- But we all know that the world is a much more complicated place....

Motivation: Needs of ν -experiments

Typical neutrino event

Incoming neutrino:

Flavor unknown

Energy unknown



Outgoing lepton:

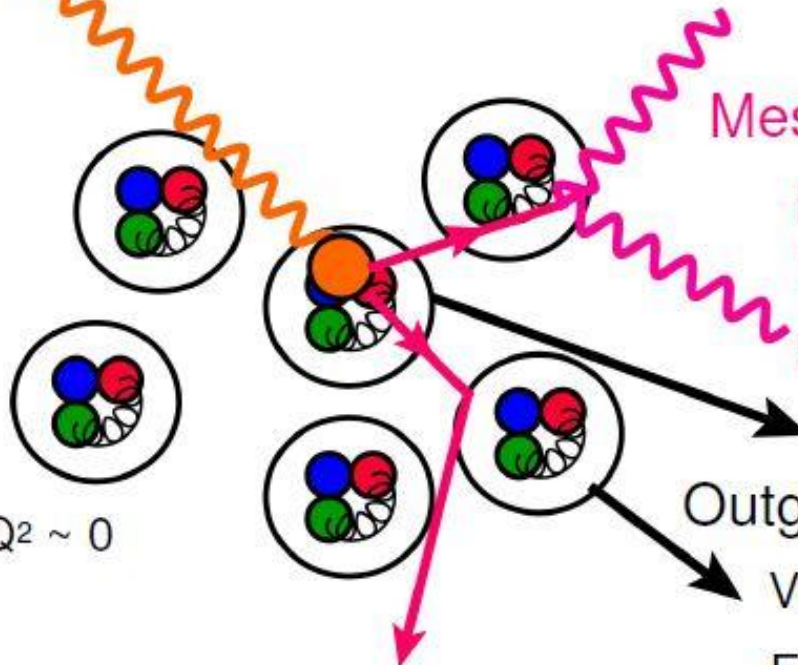
Flavor: Charge Current vs. Neutral Current, μ^+ vs. μ^- , e vs. γ

Energy: measure

Target nucleus:

Nucleus "sandbags" at $Q^2 \sim 0$

N-N correlations



Mesons:

Final State Interactions!

Energy? Identity?

Outgoing nucleons:

Visible?

Energy?